CRYOGENIC INSULATION BONDLINE STUDIES FOR REUSABLE LAUNCH VEHICLES[†]

T. F. Johnson
Mechanics and Durability Branch

E. S. Weiser
Advanced Materials and Processing Branch

NASA Langley Research Center
Hampton, VA 23681-2199

P. G. Duong
Boeing Corporation
Huntington Beach, CA 92647

ABSTRACT

Cryogenic insulations bonded to metallic substrates were characterized under simulated mission conditions representative for a reusable launch vehicle. The combined thermal and mechanical test consisted of 50 to a 100 cycles. These combined thermal and mechanical cycles simulated flight missions with temperatures ranging from -423°F to 450°F and a maximum mechanical tension load ranging from 20,000 lbs. to 97,650 lbs. The combined thermal and mechanical (uniaxial tension) test apparatus (1 ft. by 2 ft. Test Apparatus) developed at the NASA Langley Research Center, was used to perform cyclic tests on cryogenic insulations bonded to tank wall substrates. No visual delamination or degradation was observed in the cryogenic insulation-to-metallic substrate bondline or butt joints between cryogenic insulation panels. In addition, after cyclic testing was performed, residual property results from tension-pull and closed-cell content tests of the cryogenic insulations indicated a decrease in the bondline strength and closed-cell content.

INTRODUCTION

The Reusable Launch Vehicle (RLV) Program is a partnership between the National Aeronautics and Space Administration (NASA) and aerospace industry. The goal of the RLV Program has been to develop a vehicle that is fully reusable with greatly reduced operational cost[1, 2, 3]. The thermal protection system (TPS), the insulated cryogenic propellant tanks, crew/payload compartments, engines, and control systems require careful consideration for the vehicle to be viable since future launch vehicles must be fully reusable to reduce the cost of space access. However, one of the most crucial issues being considered is the development of durable, lightweight, cryogenic propellant tanks.

The cryogenic propellant tank must be leak free, capable of sustaining flight loads, and insulated. Cryogenic insulation (CI) on a propellant tank must be present to minimize boil-off of cryogenic fuels and prevent the liquefaction of air or oxygen on the surface of the vehicle, cryopumping, frost or ice build-up, and phase changes of adhesives if the TPS is adhesively bonded to the CI. Typical CIs are closed-cell foams that are sprayed on or bonded to the external surface of the tank. CIs are generally brittle and are prone to cracking under repeated exposure to thermal stresses induced by temperature gradients and transients, and to membrane and bending stresses due to pressurization loads. A thorough investigation of the influence of the thermal and mechanical stress conditions on the CI compatibility with a substrate is the primary objective of this paper.

Testing was conducted at NASA Langley Research Center (LaRC) on four panels to evaluate strain compatibility of the reusable CI test specimen under thermal and mechanical cycling loads encountered during a sample RLV mission profile. A maximum of a 100 combined thermal and mechanical cycles was conducted (1,500 to 2,600 cycles are required for the qualification of RLV structures and materials). The cyclic experiments were performed to determine the effects of cyclic exposure to thermal gradients, thermal transients, and mechanical loading at cryogenic and elevated temperature on the bondline and CI. The durability of the proposed CI systems, the reliability of adhesive systems used to bond the CI to the tank structure, the effect of cyclic combined thermal and mechanical loading on the tank concepts (via pre-test and post-test tension-pull and closed-cell content tests), and the capability of each concept to withstand thermal gradients and transients were investigated. This paper summarizes the experimental methodology used and discusses the results.

[†] Approved for public release: distribution unlimited.

TEST SPECIMENS AND METHODS

The method for testing cryogenic foams and attachment methods through simulated missions described herein was first developed by A. H. Taylor, et. al. for the Advanced Launch Vehicle (ALS) Program[4]. A series of tests and test facilities were developed at LaRC for the X-33/RLV Program during Phase I, Thermal Structures Technology Development for RLV Cryogenic Propellant Tanks[5]. These tests were developed to verify the integrity of the cryogenic tank concepts and insulation methods under vehicle mission conditions. Either liquid oxygen (LOX) tank or liquid hydrogen (LH_2) tank structural concepts can be tested to validate the durability and reusability of the concept. This test method was used to test a Lockheed-Martin Michoud Space Systems (LMMSS) X-33/RLV LOX tank concept. A total of 50 flight mission cycles were simulated during these experiments[6].

A flight mission cycle included both thermal and mechanical loading conditions. The cryogenic side and foam side temperatures of the panel were varied, simulating cryogenic cooling and re-entry heating experienced during a flight mission. In addition to the thermal loading, the mechanical loading due to pressurization of the cryogenic propellant tank was varied[6]. Once the cyclic testing was completed residual property tests such as tension-pull and CI closed-cell content test were performed.

THERMAL MECHANICAL CYCLIC TESTING

The CI specimens were 12-in. by 12-in. by 1-in.-thick panels made of a dual foam-filled honeycomb core adhesively bonded to the metallic substrate. The CI configuration comprised of 50% polyurethane (PU) spray foam within the Nomex™ honeycomb core adjacent to the metallic substrate and 50% TEEK-H polyimide (PI) foam friable-balloons[7] within the core as shown in Figure 1.

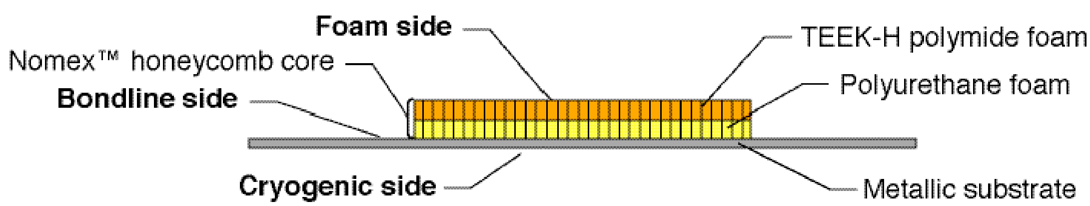


Figure 1. 50% TEEK-H PI Foam/50% PU Foam Reinforced with Nomex™ Honeycomb Core Hybrid Foam TEEK-H/PU/Nomex™

The honeycomb core material was Nomex™ with a 2-pcf density and 0.375 in. hexagonal cell size. The PI foam was cured within the honeycomb core by fusing a TEEK-H friable-balloons precursor[7]. PU foam was sprayed into the honeycomb core. Excess PU foam was removed using knives, pneumatic shavers, and the surface was sanded smooth and flush with the honeycomb core.

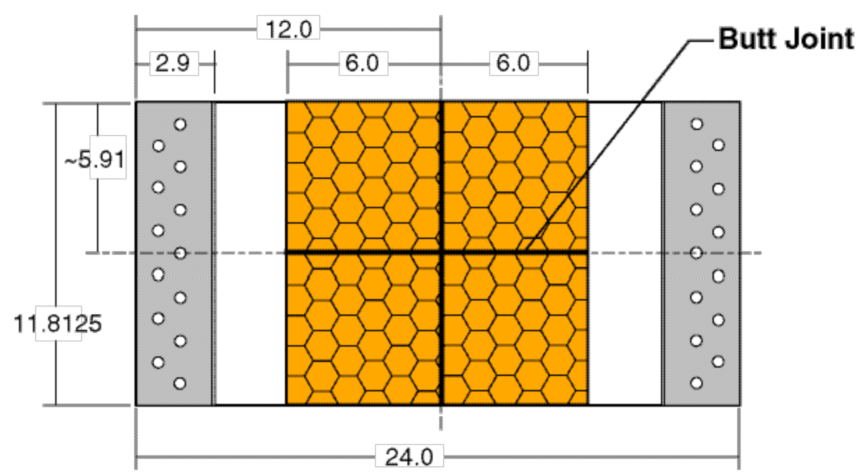


Figure 2. Panel 4 with Four Sections of CI Bonded Together with Butt Joint Using Epoxy Adhesive (Cell Size Not to Scale) (All Dimensions are in Inches)

The metal substrate for panels 1 and 2, as well as a materials allowables test specimen, was made of C-458 aluminum-lithium alloy (C-458) with dimensions of 1 ft. by 2 ft. and 0.141-in. in thickness. The substrates for panels 3 and 4 had similar dimensions but were made of 2219-T87 aluminum alloy (AL-2219-T87) and were 11.8125-in. wide and 0.375-in. in thickness. Load introduction holes were machined into the substrates as shown in Figure 3. The substrates were etched and anodized per MIL-A-8625[8] Type IIB, Class 1. A 0.5-1.0-mil-thick cryogenic corrosion-preventive epoxy primer was applied onto the bonding surfaces. A material bearing allowables test specimen was fabricated to verify that panels 1 and 2, would not be damaged by the bolt bearing loads at the maximum applied load. Panel 4 had four sections of CI, shown in Figure 2, that were spliced together with a butt joint using an epoxy adhesive.

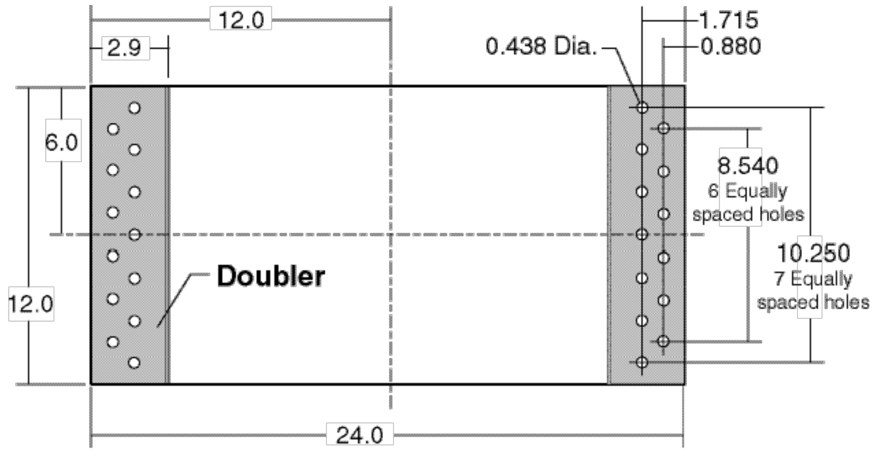


Figure 3. Schematic Drawing Illustrating Locations of Attachment Holes Machined into Metal Substrate (All Dimensions are in Inches)

Test Panel Assembly

The cryogenic side of the metal substrate was left bare to be exposed to liquid helium (LHe) cryogen during the test while the middle portion of bondline side was covered with bonded-on CI (shown in Figures 2 and 4). Prior to bonding, the primed metallic surface was cleaned and sanded to achieve a water-break free condition. The PU adhesive was used to bond the 12-in. by 12-in. CI specimens onto the C-458 or AL-2219-T87 metal substrate. A uniform thickness (~10-15 mils) of the PU adhesive was applied onto the CI bonding surface. Finally, a vacuum bag was sealed over the test panel with 10-inches of Hg vacuum applied. The PU adhesive was allowed to cure until a minimum Shore-A hardness of 50 was attained.

Panel Instrumentation

Each panel assembly was instrumented with one strain gage (WK-13-250BG-350) and 23 thermocouples (TCs) (Type E and K), as shown in Figure 4. A list of the strain gage and thermocouple locations for the panels is provided in Table 1. Strain Gage 12S uses TC 12E as a reference temperature TC.

All of the strain gage and TC wires were Teflon™ coated and were 17-ft. in length. A 24-gage wire was used in areas external to the bondline. Within the CI-to-metallic substrate bondline, 30-gage TC wires were used. The exit points from the foam were sealed with the PU adhesive bondline squeeze-out. The TC wires and beads were attached to the panel using aluminum tape and/or RTV 560 silicone adhesive.

Test Apparatus

A schematic of the 1 ft. by 2 ft. test apparatus is shown in Figure 5. The test article was mounted in a MTS[+] or Shore Western, Inc. (SW) universal test stand with a load capacity of 220 kips. The 1 ft. by 2 ft. test apparatus in the MTS test stand is shown in Figure 5. A cryogenic cooling apparatus and a heating apparatus are sandwiched around the test specimen. A Watlow Anaphaze™ controller controlled the temperatures on the external surfaces of the insulation (foam side) and the panel substrate (cryogenic side). A MTS 458 controller operating in load control mode, controlled the mechanical load. Dewars of LHe and liquid nitrogen (LN_2) supplied the cryogenic fluid to cool the test article during the tests.

[+] Use of a trade name or product is not an endorsement by the NASA.

Table 1. Instrumentation for the Test Panels

Sensor no.	Type	Location	Sensor no.	Type	Location
1E	Type E TC	Bondline side	12E	Type E TC	Cryogenic side
2E	Type E TC	Bondline side (under foam)	12EE	Type E TC	Cryogenic side
3E*	Type E TC	Bondline side (under foam)	12S**	Strain Gage	Cryogenic side
3EE	Type E TC	Bondline side (under foam)	13K*	Type K TC	Cryogenic side
4E	Type E TC	Bondline side (under foam)	14E	Type E TC	Cryogenic side
5E	Type E TC	Bondline side	15E	Type E TC	Cryogenic side
6E	Type E TC	Cryogenic side	16E	Type E TC	Cryogenic side
7E*	Type E TC	Cryogenic side	17E*	Type E TC	Cryogenic side
8E	Type E TC	Cryogenic side	18K	Type K TC	Foam side
9E	Type E TC	Cryogenic side	19K	Type K TC	Foam side
10E	Type E TC	Cryogenic side	20K*	Type K TC	Foam side
11K*	Type K TC	Cryogenic side	21K	Type K TC	Foam side

* TCs 3E, 7E, 11K, 13K, 17E, and 20K are used for the "Temperature Control System" and are not recorded for data acquisition.

** TC 12E was the reference thermocouple for strain gage 12S.

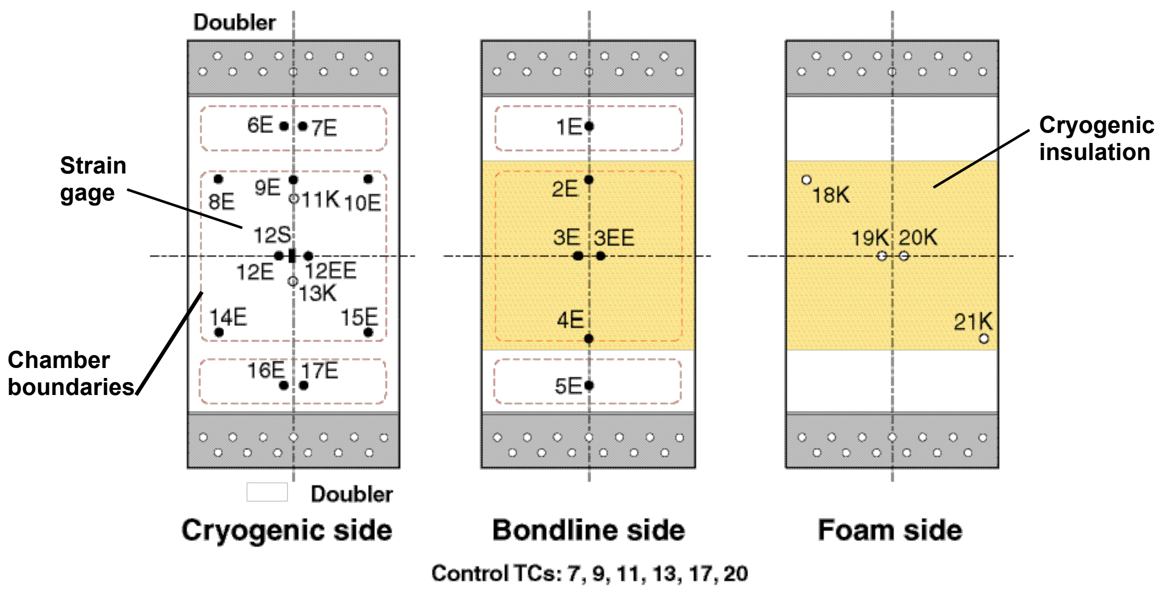


Figure 4. Instrumentation Pattern and Location of CI on the Boeing 1 ft. by 2 ft. Specimen

The cooling apparatus, located on the aluminum face of the panel, consisted of three insulated cryogenic chambers sealed to the test panel with a 0.5-in.-wide Gortex™ gasket material. This gasket material was made of expanded polytetrafloraletheline (EPTFE) and remained flexible at cryogenic temperatures. The top and bottom chambers were filled with LN_2 to prevent the flow of heat into the center region of the test panel from the load introduction structure. The center chamber was filled with LHe during the cryogenic phase of testing.

The external surface of the foam was heated by convection using an insulated convection chamber, shown in Figure 5. The convection chamber was sealed to the surface of the foam with a 0.5-in.-wide glass-fiber rope. Four 6-in.-long fin-strip heaters mounted to the sides of the heater chamber supplied heat. Each of the heaters was rated at 150 watts and was operated using a 220 volts supply. A 100 cubic feet-per-minute (CFM) fan circulated air in the chamber to transfer heat from the fin-strip heaters to the surface of the panel. Cool gaseous nitrogen (GN_2) was also supplied to the chamber to prevent overheating of the specimen.

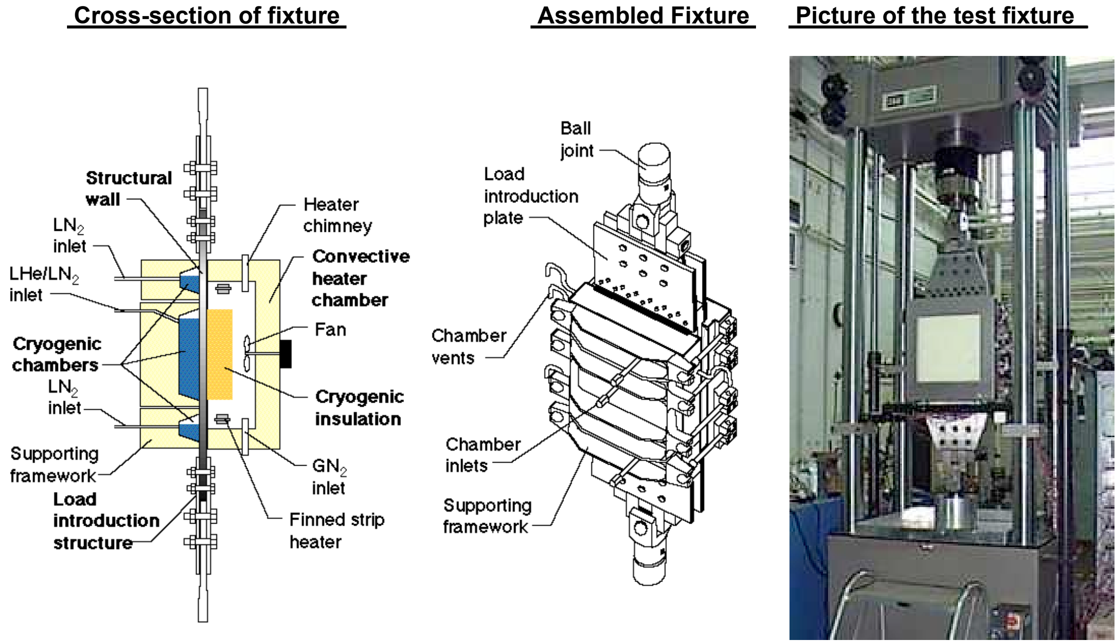


Figure 5. **Cross-Section Schematic View, Assembled View, and Picture of the MTS Test Fixture for the 1 ft. by 2 ft. Test Apparatus**

Test Procedures

The simulated flight mission was repeated for 50 to a 100 cycles to assess the response of the structural insulation exposed to combined thermal and mechanical cyclic loading. If the panel, foam, or bondline degraded significantly, the panel was removed from the test stand. The flight mission profile used in these tests is plotted in Figure 6 and is detailed in Table 2.

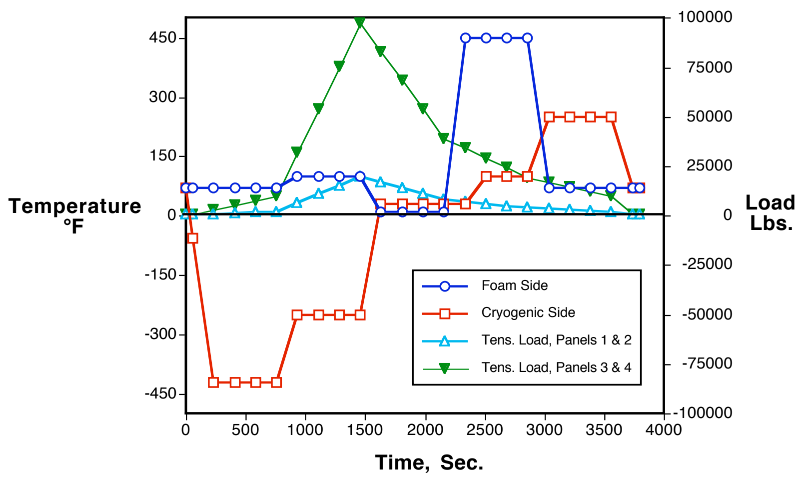


Figure 6. **Plot of the Flight Mission Profile used in the 1 ft. by 2 ft. Testing**

Flight Mission Simulation

The panel was mounted in either the MTS or SW test machines and the following steps were used to execute typical flight mission simulations:

1. Verify that the conventional instrumentation is functional.
2. Initialize the heating and cryogenic system and test machine.
3. Apply an initial loading of 500 lbs.
4. Start recording all conventional instrumentation readings at two scans per min. at Time = 0 secs.
5. Chill the test aluminum face of the panel to -423°F in 5 mins. while maintaining an external insulation face temperature of 70°F. Maintain these temperatures until a steady-state condition is achieved. Hold the

steady-state condition for 5 minutes.

6. Increase the recording rate for the conventional instrumentation to one scan per sec. at Time = 525 secs.
7. Apply the thermal/mechanical load profile shown in Figure 6 and listed in Table 2.
8. Decrease scan rate to one scan every 30 secs. at Time = 2,510 secs.
9. After completing the profile, maintain the 500 lb. tensile load and begin steadily cooling the foam surface and aluminum substrate of the panel until both surfaces achieve a minimum temperature of 70°F using cool GN_2 as a purge gas.
10. Stop recording conventional instrumentation data at Time = 3,800 secs.
11. Visually inspect the test panel.

Perform additional flight mission cycles by repeating step (1) through (11) until a total of 50 or a 100 cycles have been applied.

Table 2. Set Points Used for the 1 ft. by 2 ft. Panel Flight Profile Testing

Time		Foam side temp. (°F)	Cryo side temp. (°F)	Tension load (Lbs.)		Segment time (Sec.)	Notes
(Mins.)	(Sec.)			Panels 1 & 2	Panels 3 & 4		
00:00	0	70	70	500	500	60	Cool down
01:00	60	70	-56	500	500	175	Ground hold
03:55	235	70	-423	875	2816	175	Ground hold
06:50	410	70	-423	1250	5133	175	Ground hold
09:45	585	70	-423	1625	7450	175	Ground hold
12:40	760	70	-423	2000	9766	175	Ground hold
15:35	935	100	-250	6500	31736	175	Ascent
18:30	1110	100	-250	11000	53706	175	Ascent
21:25	1285	100	-250	15500	75676	175	Ascent
24:20	1460	100	-250	20000	97646	175	Ascent
27:15	1635	10	30	17000	82999	175	Orbit
30:10	1810	10	30	14000	68352	175	Orbit
33:05	1985	10	30	11000	53705	175	Orbit
36:00	2160	10	30	8000	39058	175	Orbit
38:55	2335	450	30	7000	34176	175	Re-entry
41:50	2510	450	100	6000	29294	175	Re-entry
44:45	2685	450	100	5000	24412	175	Re-entry
47:40	2860	450	100	4000	19530	175	Re-entry
50:35	3035	70	250	3500	17089	175	Soak through
53:30	3210	70	250	3000	14648	175	Soak through
56:25	3385	70	250	2500	12206	175	Soak through
59:20	3560	70	250	2000	9765	175	Soak through
1:02:15	3735	70	70	500	500	175	Cool down
1:03:15	3795	70	70	500	500	60	Cool down

RESIDUAL PROPERTY TESTS

Tensile-Pull Test

Tensile-pull testing was conducted on test panels 1 and 2 by Boeing after LaRC applied the ~50 cycles of combined thermal and mechanical loading to quantitatively assess the CI-to-metallic substrate bond strength. Panels 3 and 4 are currently being cycled a 100 times and not yet ready for post-test evaluation. Two-inch diameter samples were cored out from the CI while the CI was still bonded to the C-458 substrate of the panel. The cored-samples were bonded to 2-inch-diameter aluminum blocks using an epoxy adhesive. A portable piston assembly was mechanically attached to the threaded aluminum block and GN_2 gas pressure in the piston was steadily increased until there was failure in the CI core sample.

Closed-Cell Content Tests

The proportion of closed to open cells in a given foam material quantifies the resistance of the foam to gas flow. In theory, higher closed-cell content diminishes foam damage should cryopumping occur. The phenomenon of cryopumping pertains to the pumping of gas into the foam and subsequent condensation into a liquid during thermal cycling[9]. Cryopumping can damage foam cells and thus reduce the thermal and structural characteristics of the foam.

The closed-cell content of the three CI material configurations PI, PU, and PU/PI was tested per ASTM D-6226 at room temperature in gaseous nitrogen (GN_2) using a Quantachrome Ultrapycnometer 1000 by the Boeing/HB Thermal Management Systems (TMS) laboratory. Post-test evaluation of the closed-cell content for panels 3 and 4 were performed at LaRC according to ASTM D -6226 utilizing a Quantachrome Ultrapycnometer 1000. The nominal dimensions of the CI specimens were 1.0-in by 1.0-in by 1.0-in cubes[7].

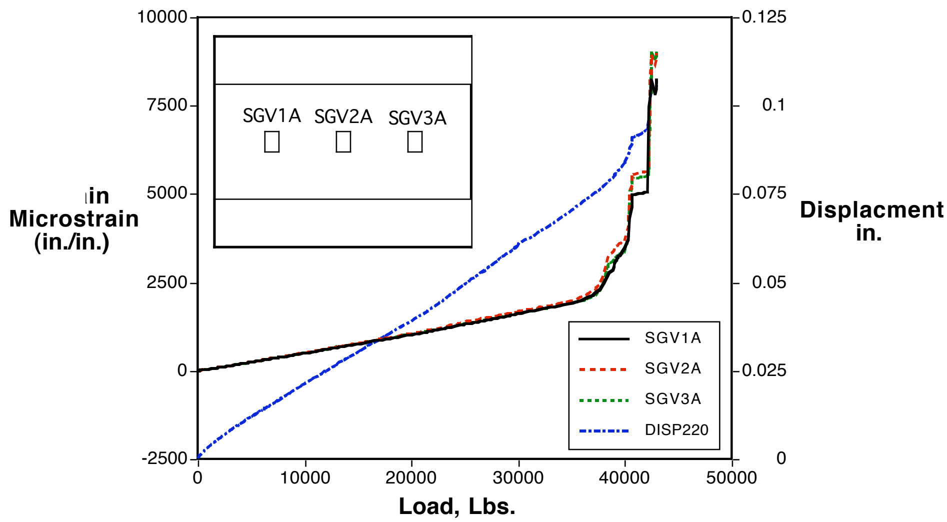


Figure 7. Plot of the Applied Load Versus Axial Strain and Displacement for the Bearing Allowables Specimen

RESULTS AND DISCUSSIONS

Experimental results for the material allowables panel test and flight mission simulations for panels 1 through 4 are presented here. All 1 ft. by 2 ft. specimens were tested for 50 to a 100 cycles with each cycle lasting over 63 minutes. The panels were exposed to greater than 50 or 100 cycles due to errors encountered in the running of the cycle such as the absence of applied mechanical load or less than adequate amount of LHe. If a cycle had either of these two situations occur, the cycle was repeated but still counted. The experimental data reported include histories of temperature and mechanical load for two typical mission simulations, the first and 57th cycle for panel 1 and the 55th cycle for panel 4. The data for all other cycles and panels are similar and are not reported. Photographs of the test panel taken as testing progressed are also shown here. The residual property results from tensile-pull and closed-cell content tests are also presented.

MATERIALS ALLOWABLES TESTING

The maximum load for the bolt bearing allowables specimen was calculated to be 82,000 lbs. When the first allowables specimen was tested, the specimen failed at approximately 32,000 lbs. Aluminum 6061-T6 doublers were bonded to the substrate of the allowables specimen with EA-9394 epoxy adhesive.

A plot of the specimen load versus strain and displacement results for an allowables specimen is shown in Figure 7, where the material yielded at approximately 37,000 lbs. The maximum strain corresponding to this load was 2,200 □□.

It was determined subsequently, that the C-458 material used in the allowables specimen was an annealed version of the desired material. Based on these results, the maximum load for panels 1 and 2 was adjusted to reflect the reduced material properties and aluminum 6061-T6 doublers were bonded to both specimens with EA-9394 epoxy adhesive. Panels 3 and 4 had integrally machined doublers on each end. Boeing analytically estimated the bolt bearing capability of panels 3 and 4 while LaRC verified the bolt bearing capability by mechanical testing, before the combined thermal and mechanical cyclic tests were conducted.

FLIGHT MISSION SIMULATION TESTING - PANELS 1 AND 2

Temperature and load data from flight mission cycle 1 and cycle 57 for panel 1 are shown in Figures 8 and 9. Panel 2 had similar results and the data was not presented. The controller segment duration times and temperatures were modified to achieve a profile similar to the profiles plotted in Figure 6.

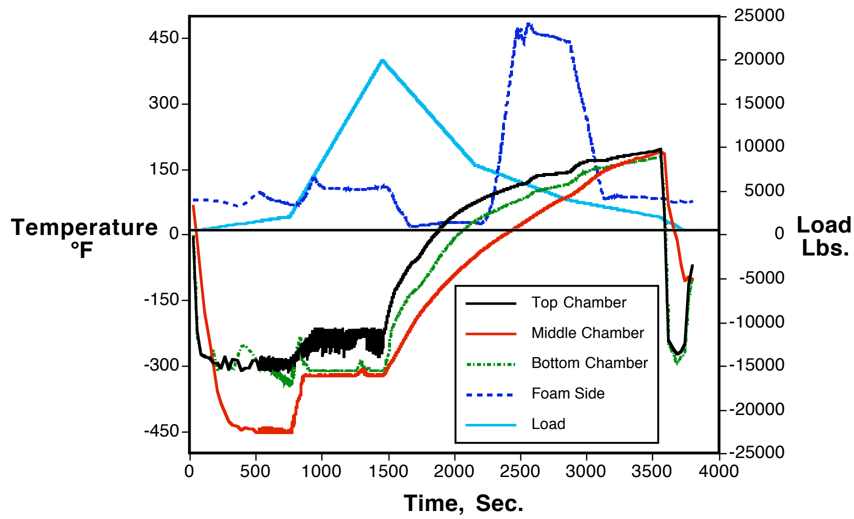


Figure 8. **Time Versus Temperature and Load for Cycle 1 of Panel 1 in the 1 ft. by 2 ft. Test Apparatus**

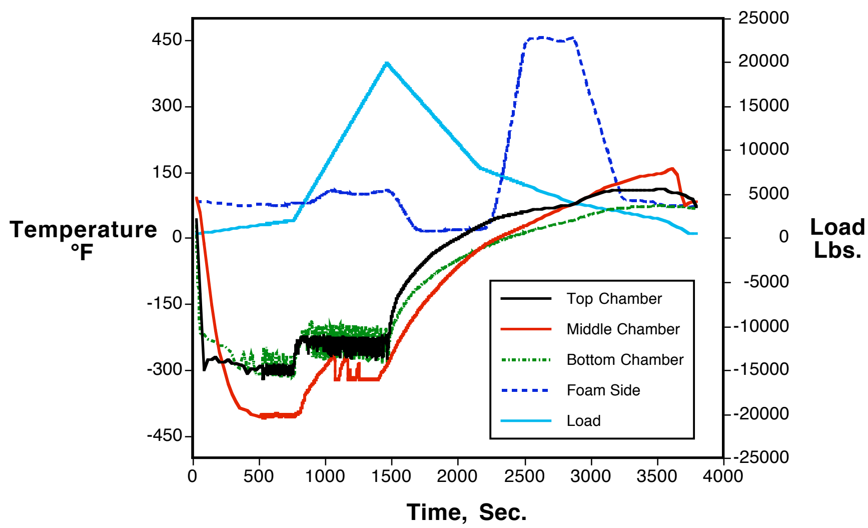


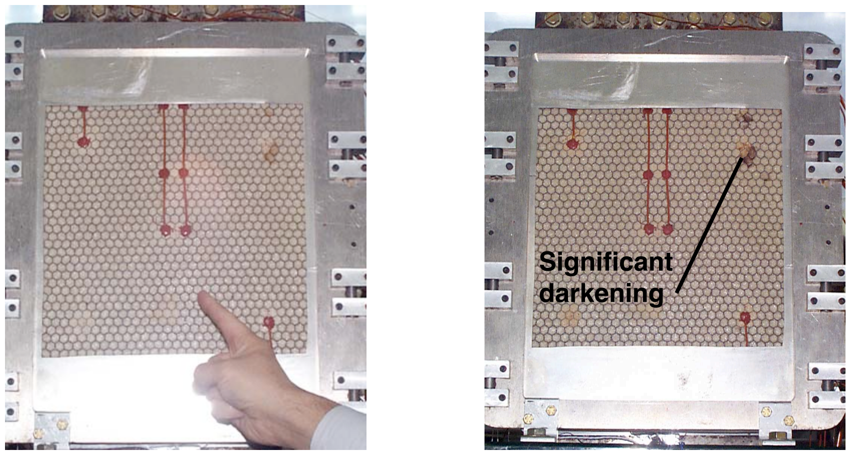
Figure 9. **Time Versus Temperature and Load for Cycle 57 of Panel 1 in the 1 ft. by 2 ft. Test Apparatus**

The temperature of the cryogenic side of the test specimen (middle temperature in Figure 5) decreased to -423±10°F within 5 minutes. The cryogenic side temperature and the bondline temperature were maintained at -423±10°F for 875 seconds (14:35 minutes). At 935 seconds (15:35 minutes) into the mission, the foam side was heated to 100±10°F in 175 seconds (2:55 minutes) and the cryogenic side was heated to –250±10°F. The foam side and cryogenic side were held at this temperature for 525 seconds (8:45 minutes). At 1,635 seconds (27:15 minutes) the foam side temperature was decreased to 10°F in 175 seconds (2:55 minutes) and the foam side was heated to achieve 30°F. The cryogenic side temperature increased for the remaining portion of the cycle to 150°F at the time 3,560 seconds (59:20 minutes), but was less than the prescribed 250°F. At 2,335 seconds (38:55 minutes), the foam side temperature was increased to 450±10°F in less than 350 seconds (5:50 minutes). The foam side was held at this temperature for 350 seconds (5:50 minutes). However, due to thermal control problems, there were cycles when the external surface of the foam was heated to above 550°F. This over-temperature condition occurred as the thermal control system was tuned. No visual signs of degradation were observed due to this over-temperature condition. The temperature on all surfaces was decreased at 2,860 seconds (47:40 minutes) to 70±10°F and held at constant temperature until the end of the cycle. At the end of the cycle all heating was stopped in the test chambers and the chambers were purged with LN_2, cooling the substrate to room temperature (70°F) for the start of the next cycle. The entire mission cycle with the initial cool down and post cooling lasted 3,795 seconds (1 hour, 3:15 minutes).

The mechanical load level was held constant at 500 lb. for 60 seconds (1 minute) and then ramped up to 2,000 lbs. in 875 seconds (14:35 minutes). The load was then increased to a peak value of 20,000 lbs. in 700 seconds

(11:40 minutes). During the first phase of the test, the panel underwent a thermally induced contraction to a maximum displacement value of -0.811 in. The panel was elongated under tension load to a peak displacement value of 0.612 in. during the next phase of the simulation (when the peak tensile load was applied). At 1,460 seconds (24:20 minutes), when peak tensile load was applied, the bondline strains increased to peak values of 1,040±100 □□. As the panel was unloaded and as the surface temperatures returned to room temperature, the strain returned to the initial unstrained magnitudes.

Photographs of the specimens were taken during the combined thermal and mechanical cycle testing. The photographs of panel 1 before cycle 1 and after the last cycle are shown in Figure 10.



Before cycle 1 **After cycle 57**

Figure 10. Photographs of the Upper Surface of Panel 1 Before Cycle 1 and After Cycle 57

<u>FLIGHT MISSION SIMULATION TESTING - PANELS 3 AND 4</u>

The thermal profile for testing panels 3 and 4 was the same as the thermal profile for panels 1 and 2. Flight mission cycle 55 for panel 4 is shown in Figure 11. The load profile for testing panels 3 and 4 had a peak load of 97,650 lbs, which was higher than the peak load for testing panels 1 and 2. The load level was held constant at 500 lb. for 60 seconds (1 minute) and then ramped up to 9,766 lbs. in 875 seconds (14:35 minutes). The load was then increased to a peak value of 97,650 lbs. in 700 seconds (11:40 minutes). During the first phase of the test, the panel underwent a thermally induced contraction to a maximum displacement value of -0.043 in. The panel was elongated under tension load to a peak displacement value of 0.167 in. during the next phase of the simulation (when the peak tensile load was applied). At 1,460 seconds (24:20 minutes), when peak tensile load was applied, the bondline uncorrected strains increased to peak values of 4,233±100 □□ strain.

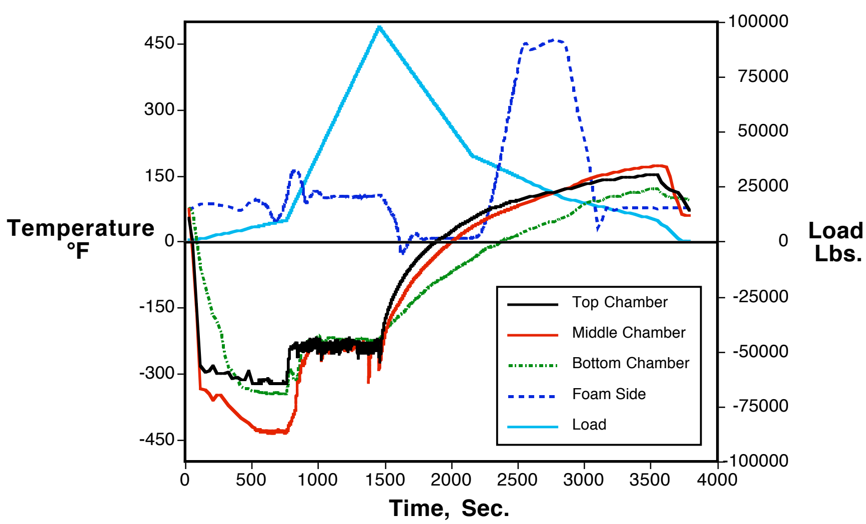
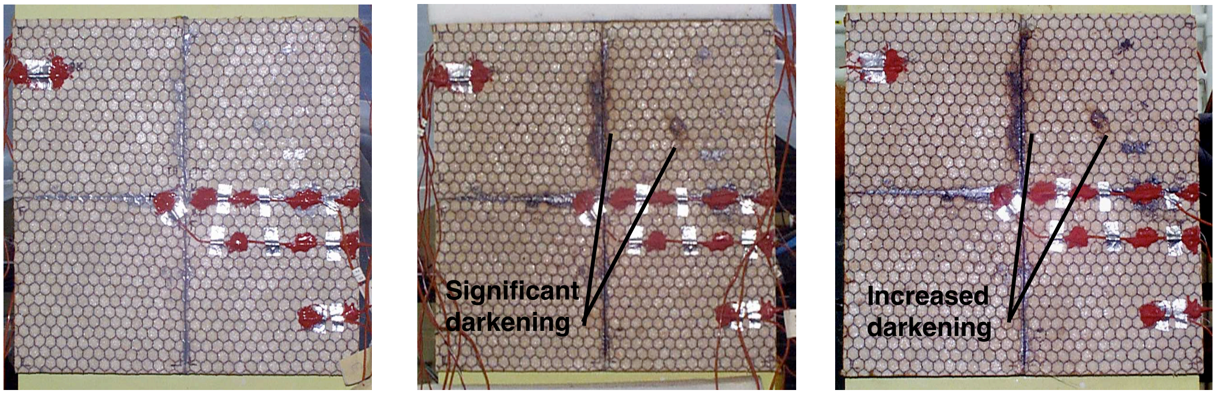


Figure 11. Time Versus Temperature and Load for Cycle 55 of Panel 4 in the 1 ft. by 2 ft. Test Apparatus

Photographs of panel 4 were taken before the first cycle, halfway through the course of cyclic testing at cycle 55, and at the end of the test after cycle 117. These pictures are presented in Figure 12.



Before cycle 1 **After cycle 55** **After cycle 117**

Figure 12. Photographs of the Upper Surface of Panel 4 Before Cycle 1, After Cycle 55, and After Cycle 117

All four test panels completed the combined thermal and mechanical cyclic testing with little visual evidence of damage or degradation. The thermal and mechanical loading closely matched the prescribed conditions specified by Boeing except for the heating phase on the cryogenic side where the heating ramp rate desired was beyond the capability of the thermal control system. Additional cycles were rerun to account for cycles where a run error occurred. A reduced mechanical load (lower strain) was applied to panels 1 and 2. The reduced load was selected due to the lower material properties of the annealed C-458. There were no signs of degradation anywhere on the specimen during the tests or when the panel was removed from the test stand. In Figures 11 and 12 there were no signs of visual physical degradation except for the slight darkening of the upper surface of the specimen and the charring or melting of any substances left on the upper surface of the TEEK-H/PU/Nomex™ CI. Darkening did occur on the surface of panel 4 after the 55th and 117th cycles, as shown in Figure 12, with substantial darkening of the butt joint epoxy adhesive.

TENSILE-PULL TESTING

The failure modes of the tested pull-plug samples are shown in Figure 13. Table 3 lists the unexposed baseline tensile-pull strength values with the averaged post-test values for panels 1 and 2.

Table 3. Average Tensile-Pull Testing Results

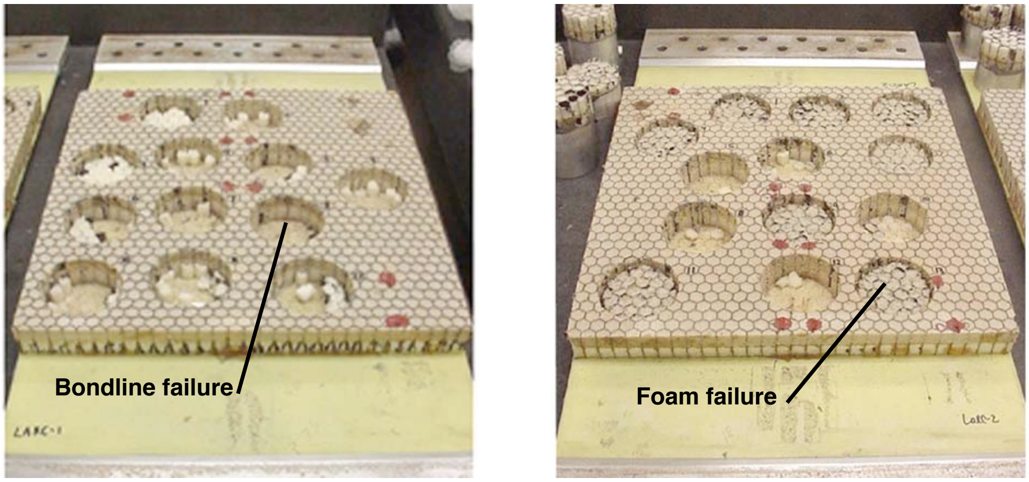
Specimen	No. of cycles	Average strength (psi)	Standard deviation (psi)	Percent diff. from baseline (%)
Not cycled	N/A	90.1	8.6	N/A
Panel 1	57	74.7	11.8	17.1
Panel 2	54	89.7	11.3	0.444
Panel 3	114	TBD	TBD	TBD
Panel 4	117	TBD	TBD	TBD

Although both panels were prepared in the same manner, no loss in bondline tension strength due to cycling was noted for panel 2 while bondline strength loss was observed in panel 1. As shown in Figure 13, the tensile-pull tests in panel 1 exhibited failures at the substrate and the adhesive bondline than for panel 2, indicating that the adhesive for panel 1 may have degraded due to the combined thermal and mechanical cyclic exposure.

CLOSED-CELL CONTENT TESTING

The closed-cell content test results are provided in Table 4. The “corrected” data accounts for the artificially created open cells on the edges of the closed-cell CI produced by the cutting process. A comparison of the post-test closed-cell results for the TEEK-H/PU/Nomex™ CI to the pretest value is in Table 5.

The high closed-cell content of the PU foam is consistent with results reported here and those published in the literature for this material[9]. Although a relatively lower (~66%) closed-cell content for the TEEK-H foam is expected, this value is substantially higher (~30%) than the value reported in previous PI foam development efforts[7]. The increased closed-cell content for the TEEK-H foam may be attributed to the improved fabrication developed for PI panels. The inclusion of the Nomex™ honeycomb did not seem to impact the closed-cell content significantly of the overall TEEK-H/PU/Nomex™ system. The closed-cell content appears to reflect the core fill constituents rather than the honeycomb core. The residual closed-cell content results in Table 5 indicate that on an average, combined thermal and mechanical cycling decreased the closed-cell content of the TEEK-H/PU/Nomex™ CI by 12.2%.



Panel 1 **Panel 2**

Figure 13. Cavities in Panels 1 and 2 after Post Cyclic Testing Tensile-Pull Tests

Panel 2 had the lower decrease in closed–cell content at 2.2% while panel 1 had the greatest at 18%. Panels 3 and 4 had a comparable decrease in closed-cell content of 14%, lower than the closed-cell content for panel 1, even though panel 1 was exposed to 50 cycles.

Table 4. Pretest Closed-Cell Content of the CI Constituents

Specimen No.	Closed-cell content (%)		
	TEEK-H	PU	TEEK-H/PU/Nomex™
1	64.6	95.4	68.5
2	63.8	95.8	68.6
3	67.5	94.6	72.3
4	67.3	95.4	68.9
5	-	-	72.1
6	-	-	70.3
Average	65.8	95.3	70.12

Table 5. Comparison of Pre- and Post-test Closed-Cell Contents of TEEK-H/PU/Nomex™

Panel No.	No. of cycles	Average closed-cell content (%)	Standard deviation (%)	Difference w/baseline (%)	Percent diff. from baseline (%)
Non Cycled	-	70.1	-	-	-
1	57	56.9	3.5	13.2	18.8
2	54	68.5	2.0	1.6	2.2
3	114	60.4	4.5	9.7	13.8
4	117	60.3	3.5	9.8	14.0

CONCLUDING REMARKS

Uniaxial tension tests were conducted on four panels with combinations of bonded cryogenic insulations (CI) and adherents to evaluate the bondline integrity under combined thermal and mechanical loading conditions. The combined thermal and mechanical cyclic loading simulated reusable launch vehicle (RLV) flight profiles. Post-test evaluations were performed to determine the residual tension-plug pull strength and closed-cell content.

The TEEK-H/Polyurethane/Nomex™ hybrid CI subjected to combined thermal and mechanical cyclic loading exhibited no apparent visual degradation. Although there was a slight darkening of the upper surface of the foam for all four panels and marked darkening of the epoxy adhesive at the CI butt joints for panel 4. There were no visible signs of material loss or degradation in the CI surface or exterior edges of the bondlines after the panels were subjected to 50 or 100 combined thermal and mechanical flight cycles.

The post-test residual property tests for tensile-pull strength results indicated that there was degradation in the adhesive bondline for panel 1 and no degradation of the bondline for panel 2. Closed-cell content tests of the CIs for panels 1 and 2 after the cyclic tests indicate that the CI on panel 1 had degraded by 18% due to ~50 combined thermal and mechanical cycles. The closed-cell content for panels 3 and 4 decreased by 14% after ~100 cycles.

These results suggest that combined thermal and mechanical cyclic testing is essential to verify of the durability of the CIs and the integrity of the CIs and adhesive bondlines. Also, based on the 50 to 100 cycles to which the testing was conducted for the panels, a full test from 1,800 to 2,600 cycles is expected to result in more significant degradation to the closed-cell content and CI-to-metallic substrate bondline strength.

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